SYSTEM FOR TRANSPORTING AND SELECTIVELY SORTING PARTICLES AND METHOD OF USING THE SAME

[0001] The present invention broadly relates to the art of material handling and processing and, more particularly, to a system and method for transporting particles and selectively sorting the same during transport.

Background of the Invention

[0002] The present invention relates broadly to the art of transporting and selectively sorting minute particles, such as fine powders, for example. It finds particular application in conjunction with the handling and processing of pharmaceutical and non-pharmaceutical ingredients and compounds, and will be described herein with particular reference thereto. However, it is to be specifically understood that the present invention can be used in a wide range of other applications, and is equally applicable in a variety of other industries, such as biotechnology, chemical production and processing and other material handling and processing applications, for example. As such, the present invention is not intended to be in any way limited or constrained to uses and/or applications within the pharmaceutical industry.

[0003] In the pharmaceutical industry, as well as other industries, there is a need for bulk quantities of uniformly sized particles. Such particles are commonly in the form of dry powders, and typically possess an electrostatic charge. In the production of medicines, for example, the uniformly sized particles are important for both intermediate processing during manufacturing, for producing products having the proper dosage and for timed-release of medication during usage. Unfortunately, bulk

quantities of ingredients and compounds often include particles in a wide variety of sizes. For example, particles having a dimension ranging from about 1.0 μm to about 100 μm are common. As such, it is commonly desirable to separate or sort the particles into two or more groups according to size.

[0004] Typically, the sorting of bulk quantities of particles is accomplished using mechanical devices, such as sieves, screens and/or other sizing machines. There are numerous disadvantages that are commonly associated with the use of such equipment. One such disadvantage is that commonly associated with mechanical equipment in general. That is, mechanical devices have moving parts that require maintenance and repair. This causes losses due to decreased production, as well as the direct costs of such maintenance and repairs.

[0005] Another disadvantage of mechanical sorting devices is that the same can create fines or fragments of particles. These can cause screens in mechanical sorting devices to become clogged, and can also negatively effect the quality and consistency of the sorted particles.

[0006] Still another disadvantage of traditional mechanical devices is that conveyors or other similar material moving devices are required to move the bulk particles from one sorting machine to the next, as the particles become more and more separated. This adds additional costs and complexities to the system.

[0007] Devices suitable for transporting bulk quantities of particles, such as toner for copy machines, for example, have been developed that use electrostatic traveling waves to move the particles. While these devices overcome some of the disadvantages of mechanical conveyors, devices using electrostatic traveling waves have to date presented shortcomings that have limited their utility. One shortcoming is that for image development, these devices often require particles having specific

characteristics, such as a certain electrical charge magnitude, polarity or other property, for example.

[0008] Other traveling wave arrangements are based on the use of dipolar forces. One disadvantage of such arrangements is that these devices commonly operate using very high voltages, such as about 2000 V, operate at very high frequencies, such as about 10-100 Mhz, and require very fine line pitches between conductors, such as about 10 μm or less, for example. Additionally, these types of traveling wave devices do nothing to overcome the disadvantages of mechanical sorting devices.

Summary of the Invention

[0009] In accordance with the present invention, a system and method for transporting and selectively sorting particles during transport is provided and can be used in various applications, such as the manufacture of pharmaceutical and non-pharmaceutical products, for example. The system and method of using the same avoid or minimize the problems and disadvantages encountered in connection with known systems and devices of the foregoing character, while promoting the efficient transport and sorting of particles without the use of mechanical moving parts, and while maintaining a desired simplicity of structure and economy of manufacture.

[0010] More particularly in this respect, a system for transporting and selectively sorting particles is provided. The system includes a first wall and a traveling wave grid extending along the first wall. The system also includes a second wall that has a passage extending therethrough. A gate is operatively associated with the passage, and a controller is provided that is in electrical communication with the traveling wave grid and the gate. The controller is adapted to provide a multi-phase electrical signal to at least one of the traveling wave grid and the gate.

[0011] Additionally, a system for transporting and selectively sorting particles is provided that includes a housing having a first wall that at least partially defines a first transport channel and a second wall at least partially defining a second transport channel. A gating passage extends in fluid communication between the first and the second transport channels. The system also includes a traveling wave grid disposed along the first transport channel, and a gate operatively associated with the gating passage. A voltage source is included that is in electrical communication with the traveling wave grid and the gate. The voltage source is adapted to output a multi-phase voltage signal to at least one of the traveling wave grid and the gate.

[0012] Furthermore, a method of transporting and selectively sorting particles is provided that can include the following steps. One step includes providing a first wall at least partially forming a first chamber, a second wall at least partially forming a second chamber, and a passage wall at least partially defining a passage extending in fluid communication between the first and second chambers. The step also includes providing a traveling wave grid disposed along the first wall, a gate operatively associated with the passage, and a controller in electrical communication with the traveling wave grid and the gate. The controller is adapted to output a multi-phase electrical signal to at least one of the traveling wave grid and the gate. Another step includes introducing a quantity of separable particles into the first chamber. Still another step includes applying a multi-phase electrical signal from the controller across at least a portion of the traveling wave grid inducing flow of the quantity of separable particles along the first chamber. Yet another step includes selectively gating a portion of the quantity of separable particles flowing along the first chamber into the second chamber.

Brief Description of the Drawings

[0013] FIGURE 1 is a side elevation view of one embodiment of a system in accordance with the present invention with a transport channel and gating passage and showing two modes of particle motion through the transport channel.

[0014] FIGURE 2 is a voltage pattern suitable for 4-phase operation of the traveling wave grid shown in FIGURE 1.

[0015] FIGURE 3 is a top plan view of the traveling wave grid shown in FIGURE 1.

[0016] FIGURE 4 is a top plan view of another embodiment of the traveling wave grid shown in FIGURE 3.

[0017] FIGURE 5 is a top plan view taken along line 5-5 in FIGURE 1 of the transport channel showing a traveling wave grid and particles aligned therealong during transport.

[0018] FIGURE 6 is a side elevation view of another embodiment of a system in accordance with the present invention having a plurality of transport channels and gating passages and shown transporting and selectively sorting particles.

[0019] FIGURE 7 is a top plan view of one embodiment of a uniform array of passages having operatively associated gates in accordance with the present invention shown disposed along a channel wall.

[0020] FIGURE 8 is a side elevation view of still another embodiment of a system in accordance with the present invention with a traveling wave grid and a gating passage.

[0021] FIGURE 9 is a perspective view of the support member and traveling wave grid of FIGURE 8 shown with particles aligned along the traveling wave grid during transport.

[0022] FIGURE 10 is a side elevation view, shown in cross-section, of one embodiment of a gate in accordance with the present invention.

[0023] FIGURE 10A is a side elevation view, shown in cross-section, of another embodiment of a gate in accordance with the present invention.

[0024] FIGURE 10B is a side elevation view, shown in cross-section, of still another embodiment of a gate in accordance with the present invention.

[0025] FIGURE 10C is a side elevation view, shown in cross-section, of yet another embodiment of a gate in accordance with the present invention.

[0026] FIGURE 11 is a voltage pattern suitable for gating bipolar particles using a bipolar voltage signal.

[0027] FIGURE 12 is a voltage pattern suitable for gating bipolar particles using a unipolar voltage signal.

[0028] FIGURE 13 is a perspective view of one embodiment of a gate in accordance with the present invention shown gating particles having a first common characteristic.

[0029] FIGURE 14 is a perspective view of the gate in FIGURE 13 shown gating particles having a second, different common characteristic.

[0030] FIGURE 15 is a voltage pattern illustrating a duty cycle of a 2-phase voltage signal suitable for operating a gate in accordance with the present invention.

[0031] FIGURE 16 is a graph of fractions of gated and non-gated negative particles as a function of time using positive voltage.

[0032] FIGURE 17 is a graph of negative particles gated as a function of time using positive voltage.

[0033] FIGURE 18 is a graph of gated particles as a function of time as the charge magnitude of the particles is varied.

[0034] FIGURE 19 is a graph of gated particles as a function of charge magnitude per diameter dimension, as the charge magnitude is increased as shown in FIGURE 18.

[0035] FIGURE 20 is a graph of gated particles as a function of time as the diameter dimension of the particles is varied.

[0036] FIGURE 21 is a graph of gated particles as a function of charge magnitude per diameter dimension, as the diameter is increased as shown in FIGURE 20.

[0037] FIGURE 22 is a graph of gated particles as a function of particle radius.

[0038] FIGURE 23 schematically illustrates a gate in accordance with the present invention showing particles being gated therethrough.

[0039] FIGURE 24 is a graph of gated particles as a function of time as the voltage applied to an electrode shown in FIGURE 23 is varied in magnitude.

[0040] FIGURE 25 is a graph of gated particle fractions as a function of time as the voltage applied to an electrode shown in FIGURE 23 is varied in magnitude.

[0041] FIGURE 26 is a voltage pattern illustrating applied voltage signals for various gating conditions.

[0042] FIGURE 27 is a graph of gated particle fractions as a function of time with a gate in accordance with the present invention operated using a transient response circuit as the gate is turned on.

[0043] FIGURE 28 is a graph of gated particle fractions as a function of time with a gate in accordance with the present invention operated without using a transient response circuit as the gate is turned off.

[0044] FIGURE 29 schematically illustrates gaseous fluid flow through a gate in accordance with the present invention to shut off particle flow therethrough.

[0045] FIGURE 30 is a graph of gated particles as a function of fluid flow velocity through a gate in accordance with the present invention.

[0046] FIGURE 31 is a voltage pattern illustrating applied voltage signals for shutting off particle flow through a gate in accordance with the present invention in use with gaseous fluid flow therethrough.

Detailed Description of the Invention

[0047] Turning now to the drawings, wherein the showings are for the purposes of illustrating preferred embodiments of the invention only and not for the purposes of limiting the invention, FIGURE 1 illustrates a system **100** for transporting and selectively sorting particles. System **100** includes a wall **102** at least partially forming a transport channel **104**. Another wall **106** is disposed in spaced relation to wall **102** and, in this embodiment, extends substantially parallel thereto. A traveling wave grid **108** is disposed along wall **102** and generates an electrostatic traveling wave suitable for inducing particles to move along channel **104**. A particle gating passage **110** extends through wall **106**. A gate **112** is operatively associated with passage **110** to selectively induce particles to flow through the passage and into a chamber **114** or other suitable feature disposed adjacent the passage opposite channel **104**.

[0048] System **100** also includes a power supply **116** that is in electrical communication with grid **108** and gate **112**. Power supply **116** is preferably adapted to output multi-phase electrical signals, such as voltage or current patterns, for example. One suitable voltage pattern is shown in FIGURE 2. The voltage pattern shows four voltage waves **V1**, **V2**, **V3** and **V4** spaced at 90 degree phase angles. The duty cycle **W** for each voltage wave is shown in FIGURE 2 as about being 75 percent of time unit **T**.

[0049] In the embodiment shown in FIGURE 1, power supply **116** is adapted to output AC electrical signals in four-phases with each phase applied along a different

one of electrical connectors **118**, **120**, **122** and **124**. The connectors are shown in FIGURE 1 as being in electrical communication with electrodes or conductors **126** that are arranged in an inter-digitized pattern. However, it will be appreciated that any suitable pattern or configuration can be used. A suitable insulating material **128** can optionally be provided between adjacent conductors to minimize air gaps.

[0050] As shown in FIGURE 3, conductors **126** are formed in four conductor groups **126A**, **126B**, **126C** and **126D** that are inter-digitized with one another to form traveling wave grid **108**. The conductors in FIGURE 3 extend transverse channel **104** in a substantially linear manner. Other configurations can be used, however, such as conductors **126'** of conductor groups **126A'**, **126B'**, **126C'** and **126D'** in FIGURE 4. One benefit of conductors **126'** is that the chevron shape assists in focusing the particle cloud within a central region of the transport channel. Transport channel **104** is demarcated by side walls **130**, in FIGURES 3 and 4. Particle flow along the channel is indicated by arrow **FL**, in each of FIGURES 3 and 4.

[0051] In one example of a suitable traveling wave grid, the conductors are spaced at a pitch of about 200 μm. As such, the corresponding conductor phase on each of the conductor groups are spaced apart a distance of about 800 μm, in this example. The traveling wave grid can include a base layer formed from a suitable dielectric material, such as a polyimide film, for example. One example of a suitable polyimide film is sold under the trademark KAPTON by DuPont High Performance Materials of Circleville, Ohio. One suitable thickness range for the polyimide film can be from about 25 μm to about 200 μm thick, and in one example of a suitable embodiment, the polyimide film is about 75 μm thick. The conductor groups and conductors thereof are formed from a suitable conductive material, such as gold, silver, or copper, for example. It will be appreciated, however, that any suitable conductive material can be

used, and the same are not limited to metal materials. In one example of a suitable embodiment, the conductors and conductor groups are made from copper and can be from about 1 μm thick to about 15 μm thick. The width of the conductors are often expressed as a percentage of the pitch of the grid and can be from about 10 percent of the pitch to about 50 percent of the pitch. A cover layer can also be provided along the grid covering the conductors and/or conductor groups to maintain electrical isolation from the charged particles. The cover layer can be formed from any suitable material, such as polyvinyl fluoride film, for example. One suitable polyvinyl fluoride film is sold under the trademark TEDLAR by DuPont Tedlar of Buffalo, New York. In one example of a suitable embodiment, a cover layer of TEDLAR film from about 5 μm thick to about 50 μm thick can be used. One suitable type of insulating material **128** is a non-conductive epoxy, such as those well known in the art, that can be used to fill the inter-conductor spacings and minimize the air gaps under the cover layer. It will be appreciated that the foregoing examples are merely illustrative of suitable materials and that any other suitable materials can be used.

[0052] Gate **112** includes a first electrode **132** and a second electrode **134** in spaced relation to one another. Gate **112** can optionally include a third electrode **136**, as shown in FIGURE 1. In the embodiment shown in FIGURE 1, electrodes **132** and **134** are in electrical communication with power supply **116** along connectors **118'** and **120'** that respectively extend from connectors **118** and **120**. As such, it will be appreciated that the gate operates on two phases of the four-phase output from the power supply. Third electrode **136** can be in electrical communication with power supply **116** along connector **122'** that extends from connector **122**, such that gate **112** operates on three phases. Alternately, a separate electrical signal, such as a DC voltage, for example, could be applied to the third electrode.

[0053] In operation, a particle cloud **PC** is disposed at one end of channel **104**. The cloud is typically formed of particles having two or more particle sizes and/or electrical charge magnitudes. It will be appreciated that particles having a single electrical polarity, either positive or negative, can be used. However, to maximize the capabilities and productivity of a system in accordance with the present invention, it is preferable to use a population of particles that includes particles of both polarities. However, this should not be in any way construed as a requirement or limitation of the system.

[0054] As discussed above, a multi-phase electrical signal, such as a four-phase AC voltage pattern, for example, is applied across the traveling wave grid driving an electrostatic traveling wave along the grid. The electrostatic traveling wave induces at least two modes of particle movement within the particle cloud. The velocity of transport along the grid scales linearly with the frequency of the electrical signal. In one example of a suitable electrical signal, the voltage waves can cycle at from about 1 Hz to about 5 kHz to achieve the desired particle velocity.

[0055] One mode of particle movement, termed a "hopping" mode for convenience and ease of reading, occurs as particles jump from conductor to conductor along the traveling wave grid in a manner substantially synchronous with the electrostatic traveling wave. The hopping mode is schematically shown in FIGURE 1 by arrows **HM**, and an illustration of the alignment of particles **PL** along conductors **126** (FIGURE 3), which extend from conductor groups **126A**, **126B**, **126C** and **126D**, is shown in FIGURE 5.

[0056] A second mode of particle motion, termed a "surfing" mode for convenience and ease of reading, flows along the channel above the particles in hopping mode. The surfing mode is schematically shown in FIGURE 1 by arrows **SM**. Due to

various forces and other factors, such as viscous drag forces, buoyancy forces, collisional forces and particle scattering, for example, the particles in surfing mode typically have a low agglomeration and are suspended in a state of substantial equilibrium above the particles in hopping mode. The particles in surfing mode are sufficiently distanced from the traveling wave grid to be substantially influenced by the electrostatic forces thereof. As such, the particles in surfing mode tend to flow along the channel in a manner that is slower and asyncronized to those particles in hopping mode and to the electrostatic traveling wave. As the low agglomeration particles in surfing mode flow past passage **110**, gate **112** operates to draw particles into and through the passage to be collected or further transported or sorted in chamber **114**. The gate can be configured and adjusted to draw particles having pre-determined characteristics from the low agglomeration of the particle cloud into and through the passage, as will be discussed in further detail hereinafter. Thus, the system can selectively sort particles, as the same are transported along the channel.

[0057] Another embodiment of a system **200** for transporting and selectively sorting particles is shown in FIGURE 6. System **200** includes a housing **202** having end walls **204** and **206**, a top wall **208** and a bottom wall **210** each extending between the end walls. Intermediate walls **212** and **214** extend between end walls **204** and **206**, and are shown as being substantially parallel with one another and to the top and bottom walls. However, it is to be specifically understood that other configurations can be used without departing from the scope and intent of the present invention. A first transport channel **216** extends between walls **210** and **214**. Similarly, a second transport channel **218** extends between walls **212** and **214**, and a third transport channel **220** extends between walls **208** and **212**. A traveling wave grid can be used within one or more of the transport channels. As shown in FIGURE 6, traveling wave

grids **222**, **224** and **226** are each disposed along the bottom wall of each of the channels. Additionally, one or more passages are provided through each of intermediate walls **212** and **214**, such that all three transport channels are in fluid communication with one another.

[0058] In the embodiment shown in FIGURE 6, the passages take the form of aperture arrays **228** and **230** supported on intermediate walls **212** and **214**, respectively. The aperture arrays can take any suitable form, arrangement or configuration, including uniform and/or non-uniform aperture patterns, as desired. One example of a suitable array is shown in FIGURE 7 and includes a uniform, 8 x 8 pattern of apertures **232** defined on a passage member **234** that is supported on or along wall **212** of channel **220**. The apertures can be of any suitable size, shape or configuration. For example, apertures **232** can be cylindrical and have a diameter of from about 10 μm to about 250 μm. A gate **236** of suitable size and dimension is disposed along each aperture **232**. A similar gating arrangement can be provided on aperture array **228** (FIGURE 6). The housing, in this or other embodiments, can optionally include side walls **238** and **240** further defining the channels therein, as shown in FIGURE 7.

[0059] System **200** also includes a power supply **242**. Connectors **244**, **246** and **248** extend in electrical communication from the power supply to traveling wave grids **222**, **224** and **226**, respectively. Additionally, connectors **250** and **252** extend in electrical communication from power supply **242** to the gates operatively associated with aperture arrays **228** and **230**, respectively. It will be appreciated that the power supply, traveling wave grids and gates can operate in a manner substantially identical to the multi-phase manner shown in and described with regard to power supply **116**, traveling wave grids **108** and gates **112** of FIGURES 1-5. As such, further detail

regarding the electrical configuration and operation of this embodiment is not reiterated here.

[0060] In operation, an initial particle cloud **CL1** is provided within transport channel **216** adjacent end wall **204**. In the embodiment shown in FIGURE 6, system **200** transports cloud **CL1** from one end of housing **202** to the other end. In the process of transporting the particles, the particles of cloud **CL1** are sorted into three relative size ranges indicated as fine particle cloud **CL2**, finer particle cloud **CL3** and finest particle cloud **CL4**. It will be appreciated that cloud **CL1** is substantially similar to particle cloud **PC** shown in FIGURE 1, and can includes particles that can be categorized in one of three different size ranges, generally labeled fine particles, finer particles and finest particles for convenience and readability. It will be appreciated that the size ranges can be any suitable size ranges, as desired. In an example of one embodiment, the size ranges could include fine particles having a dimension of from about 7 μm to about 10 μm, the finer particles having a dimension of from about 4 μm to about 6.9 μm, and the finest particles having a dimension of from about 1 μm to about 3.9 μm. In another example of an embodiment, the size ranges could include fine particles having a dimension of from about 20 μm to about 30 μm, the finer particles having a dimension of from about 10 μm to about 19 μm, and the finest particles having a dimension of from about 1 μm to about 9 μm. Additionally, the particles forming the initial particle cloud can have varying electrical charge magnitudes and/or differing electrical charge polarities. As an example, the particles could include a first population of particles having either a positive or negative electrical charge with a magnitude in the range of from about 15 fC to about 25 fC, another population of particles having either a positive or negative electrical charge with a magnitude in the range of about 8 fC to about 14 fC, and still another

population of particles having either a positive or negative electrical charge with a magnitude in the range of about 1 fC to about 7 fC. It is to be specifically understood, that the foregoing examples of ranges of particle size and electrical charge magnitude are simply examples of some of the characteristics and ranges of characteristics that can be used as a basis for sorting particles, and that the present invention is not intended to be in anyway limited or constrained by the foregoing examples.

[0061] Initial particle cloud **CL1** is induced to flow along channel **216** in the hopping and surfing modes discussed above. As the particle cloud flows along the channel, a gradient develops across the cloud where the finest particles will move toward the top of the cloud and the larger particles will move toward the bottom of the cloud. As the initial particle cloud continues to travel along the channel, the gradient will substantially stabilize. Eventually, a stabilized particle cloud reaches aperture array **228** and a selective portion of the initial particle cloud is gated or otherwise urged into and through apertures **232** of the aperture array. The size and electrical configuration of gates **236** disposed along each of the apertures can be optimized to gate particles within or below a pre-determined size range, as will be discussed hereinafter. As a result, a particle cloud **CL2** having particles primarily in the fine range is transported along channel **216** for further processing, finer sorting or any other desired use. Also, a new particle cloud **CL3** is formed in channel **218** that primarily includes particles in the finer and finest ranges. As particle cloud **CL3** is urged along channel **218** by electrostatic traveling waves from grid **224**, a stable size gradient once again develops across particle cloud **CL3**. Upon reaching aperture array **230**, a selective portion of particle cloud **CL3** is gated or otherwise urged into and through apertures **232** of aperture array **230**. Once again, the size and electrical configuration of the gates disposed along each of the apertures can be optimized to gate particles within or

below a pre-determined size range into channel **220** to form particle cloud **CL4**. The remainder of particle cloud **CL3**, now primarily formed of particles in the fine range, can be delivered along channel **218** for further processing, additional sorting or any other desired use. Similarly, particle cloud **CL4** can be delivered along channel **220** for further processing, additional sorting or other uses. It will be appreciated that a system in accordance with the present invention can take any suitable shape, configuration or arrangement, and can include any number of channels and aperture arrays as desired to suitably transport and sort particles.

[0062] Another embodiment of a system **300** for transporting and selectively sorting particles is shown in FIGURES 8 and 9. System **300** includes a supply housing **302** at least partially defining a supply chamber **304**. The supply chamber contains a supply of particles **PS** to be transported and selectively sorted. A supply conveyor **306**, of any suitable type or arrangement, is provided to replenish particle supply **PS** as needed. A traveling wave grid **308** is disposed within supply chamber **304**, and is supported on an external wall **310** of a support member **312**. The support member is shown in FIGURE 8 as being a substantially cylindrical, solid rod. It will be appreciated, however, that any suitable support member can be used, including non-cylindrical and/or hollow wall support members.

[0063] It will be appreciated that traveling wave grid **308** is substantially similar to the traveling wave grids discussed hereinbefore, and is formed from a plurality of conductors **314**. In FIGURE 8, the conductors are arranged as inter-digitized conductor groups **316**, **318**, **320** and **322**. Portions of the conductor groups are shown in FIGURE 8 as being arranged in concentric circles on an end wall **324** of the support member. However, it will be appreciated that any suitable arrangement can

be used, including providing a portion of one or more conductor groups along external wall **310** of support member **312**, as shown in FIGURE 9.

[0064] System **300** also includes a power supply **326** adapted to output a multi-phase electrical signal, as discussed in detail hereinbefore. Power supply **326** is in electrical communication with conductor groups **316, 318, 320** and **322** through connectors **328, 330, 332** and **334**, respectively. A passage **336** is provided through top wall **338** of housing **302**, and includes a gate **340** suitable for enabling selective particle migration through the passage. The gate is in electrical communication with power supply **326** through connectors **342** and **344**. It will be appreciated that the power supply, traveling wave grids and gates can operate in a manner substantially identical to the multi-phase manner shown in and described with regard to power supply **116**, traveling wave grids **108** and gates **112** of FIGURES 1-5. As such, further detail regarding the electrical configuration and operation of this embodiment is not reiterated here.

[0065] In operation, system **300** can transport and selectively sort particles **PS** as discussed hereinbefore. In the embodiment shown in FIGURE 8, the system can provide these particles to another chamber, cavity or channel, such as channel **216** of system **200**, for example, shown adjacent passage **336**. In such an arrangement, system **300** can act as a supply apparatus for generating the initial particle cloud **CL1**, shown in FIGURE 6, for example. System **300** can selectively gate particles from supply cloud **SC** through the passage and into channel **216**, for example.

[0066] As an electrostatic traveling wave is driven around external wall **310** of support member **312** by traveling wave grid **308**, particles **HP** closest to the conductors jump or hop along from conductor to conductor in a synchronous manner as discussed hereinbefore around external wall **310** of support member **312** as

indicated by arrow **TR**. Surfing particles (not numbered) will follow the hopping particles along the traveling wave grid, as discussed above, and can provide low agglomeration particles to form supply cloud **SC**. Alternately, the supply member can be supported a suitable distance from passage **336** for gate **340** to deliver particles in hopping mode through the passage. An illustration of particle alignment along conductors **314**, which extend from conductor groups **316**, **318**, **320** and **322**, is shown in FIGURE 9,

[0067] Various embodiments of suitable gate structures in accordance with the present invention are shown in FIGURES 10, 10A, 10B and 10C. A gate **400** is shown in FIGURE 10 as having first and second electrodes **402** and **404** that are each recessed into a wall **406** along a passage **408** extending therethrough. The electrodes are disposed in spaced relation to one another, and form opposing end portions of passage **408**. First electrode **402** is connected to a suitable multi-phase electrical source (not shown) through connector **410**, and second electrode **404** is similarly connected through connector **412**.

[0068] As shown in FIGURE 10A, another embodiment of gate **400** is formed from first and second electrodes **402** and **404**. In this embodiment, the electrodes take the form of an elongated strip or sheet, and are disposed in spaced relation to one another with wall **406** positioned therebetween. The electrodes form opposing end portions of passage **408**, which extends through both of the electrodes as well as wall **406**. As discussed above, first electrode **402** is connected to a suitable multi-phase electrical source (not shown) through connector **410** and second electrode **404** is similarly connected through connector **412**. One example of a suitable construction of such an embodiment can include wall **406** formed from a suitable dielectric material, such as about 10 μm thick to about 100 μm thick KAPTON film, for example. Both sides of

the film can be coated with a conductive metallic layer, such as a layer of gold, for example.

[0069] Still another embodiment of gate **400** is shown in FIGURE 10B. It will be appreciated that this embodiment is substantially similar to the embodiment shown in and described with regard to FIGURE 10. However, in the embodiment shown in FIGURE 10B, electrodes **402** and **404** are supported on wall **406** and not recessed thereinto. Electrodes **402** and **404** still form opposing end portions of passage **408**.

[0070] A further embodiment of gate **400** is shown in FIGURE 10C, and is substantially similar to that shown in FIGURE 10B. However, the embodiment shown in FIGURE 10C includes additional layers **414** and **416** disposed along both sides of wall **406** and respectively over electrodes **402** and **404**. It will be appreciated that layers **414** and **416** form opposing end portions of passage **408**, rather than the electrodes as in other embodiments.

[0071] The gates discussed herein can be formed from any suitable materials. For example, the electrodes can be formed from conductive metals, such as gold, silver or copper. Additionally, the wall disposed between the electrodes can be any suitable electrically insulating material, such as suitable fluoropolymers and/or polyimides, for example. One suitable polyimide is KAPTON, and suitable grades of fluoropolymers are sold under the trademark TEFLON by DuPont Teflon of Wilmington, Delaware. Additionally, layers **414** and **416** can be formed from any material suitable to meet the desired purpose of the layers. For example, where the layers are intended to facilitate cleaning, the layers could be formed from a suitable TEFLON compound or other reduced-friction material.

[0072] Gates in accordance with the present invention can operate to urge selected particles through an associated passage in any suitable manner. One example of a

suitable manner is illustrated in FIGURES 11-15, and can be applied, for example, to gate **112** in FIGURE 1. The voltage patterns shown in FIGURES 11 and 12 illustrate the polarity and relative magnitude for voltages **V1** and **V2** from time zero to T/2, then from time T/2 to T, then from time T to 3T/2. It will be appreciated that such voltage patterns can be used for any number of time cycles and/or portions of time cycles without departing from the scope and intent of the present invention. For purposes of illustration, voltage **V1** can be considered to be applied across electrode **132** of gate **112** and voltage **V2** can be considered to be applied across electrode **134**. Additionally, it will be appreciated that particles **N1**, **N2** and **P1** move from voltage **V1** toward voltage **V2** for each time period just as one or more particles would move from outside passage **110** adjacent electrode **132** to inside passage **110** between the electrodes and thereafter to outside the passage adjacent electrode **134**.

[0073] In operation, negatively charged particle **N1** is outside passage **110** but sufficiently near electrode **132**, which is positively charged at voltage **V1**, to be drawn toward the same and into passage **110** as shown at time zero to T/2. Electrode **134** is negatively charged at voltage **V2** at time zero to T/2. It will be appreciated from FIGURE 11 that the voltages applied across electrodes **132** and **134** are 180 degrees out of phase. That is, when one electrode is negatively charged the other is positively charged. As such, the gate alternately urges negatively charged particles into the passage and then positively charged particles into the passage.

[0074] At time T/2 to T, voltage **V1** of electrode **132** has changed to negative and voltage **V2** of electrode **134** has changed to positive. Additionally, positively charged particle **P1** is sufficiently close to now negatively charged electrode **132** that the particle is drawn toward the electrode and into passage **110**. During this same time, now positively charged electrode **134** draws negatively charged particle **N1** through

the passage, while positively charged electrode **132** repulses particle **N1** through the passage toward electrode **134**.

[0075] At time T to 3T/2, voltage **V1** of electrode **132** has returned to positive and voltage **V2** of electrode **134** has returned to negative. A new negatively charged particle **N2** is now sufficiently close to positively charged electrode **132** to be drawn toward the electrode and into the passage. Positively charged particle **P1** positioned between the electrodes is urged away from positively charged electrode **132** and toward negatively charged electrode **134**, thus moving particle **P1** through the passage. Additionally, particle **N1** has passed out of the passage and is urged away therefrom and into the associated chamber, cavity or channel by now negatively charged electrode **134**.

[0076] One advantage of the foregoing arrangement is that both positively and negatively charged particles are gated. This tends to maximize the throughput of the gating arrangement, leading to high-speed and efficient delivery of particles into the associated channel, chamber or cavity. As an example, a 50 μm diameter aperture has been shown to be capable of gating 50 μg/s of material from a particle cloud of about 2.4 percent particles in air by volume, with the gate operating at 400 V and 1 kHz. This translates into gating material at about 5 mg/s from a 10 x 10 array of 50 μm apertures. Located on about 100 μm centers, such an array would have a footprint of only about 1 mm by 1 mm.

[0077] As shown in FIGURE 12, gate **112** can also operate in the foregoing manner using a unipolar voltage pattern, rather than by using the bipolar voltage pattern shown in FIGURE 11. FIGURES 13 and 14 are snapshots of computer animation that illustrate the alternating manner in which a gate, such as gate **112**, operates using a voltage pattern, such as that shown in and described with regard to FIGURES 11 and

12. In FIGURE 13, electrode **132** is positively charged and electrode **134** is negatively charged. As such, positively charged particles **PP** are repelled by electrode **132** and prevented from entering the passage, while negatively charged particles **NP** are gated into the passage. In FIGURE 14, the polarity of each electrode has changed and positively charged particles **PP** are gated while negatively charged particles **NP** are repelled. FIGURE 15 illustrates the duty cycle **W** of voltages **V1** and **V2** during the use of a unipolar voltage pattern, such as that shown in FIGURE 12.

[0078] FIGURE 16 is a graph of negative particle fractions gated with positive voltage versus time. The results were obtained from conditions in which a constant supply of 400 particles in air at 2 percent by volume were gated through an aperture having a 25 μm radius with a +400V applied thereacross. The total particles in the air are shown by a solid line with circle symbols. The number of gated particles are shown by a solid line with square symbols, and the number of non-gated particles are shown by a dashed line with diamond symbols. It will be appreciated that one manner of interpreting FIGURE 16 is that the curve showing the number of gated particles can be indicative of gating efficiency or effectiveness. In FIGURE 16, about 78 percent of the particles are gated after 5 ms. However, 90 percent to 95 percent, or possibly an even greater percentage, of the particles could be gated under optimized conditions and parameters. FIGURE 17 is a graph of the number of negative particles gated with a positive voltage versus time. These results were obtained under the same conditions as described with regard to FIGURE 16. The number of gated negative particles are shown as a solid line having circle symbols. A curve showing the particle supply is indicated by a dashed line with square symbols.

[0079] FIGURE 18 is a graph of particles gated versus time for particles having various charge magnitudes. The results were obtained from conditions in which a

constant supply of 400 particles in air at 2.4 percent by volume were provided. Generally, the particles had a radius of about 2.9 μm and were gated through a two-phase aperture having a 50 μm diameter with two electrodes spaced 25 μm apart. The gate operated at +400V. A curve showing the gating of particles having a charge magnitude of -0.77fC is shown by a solid line having circle symbols. A curve showing the gating of particles having a charge magnitude of -1.54fC is shown by a dotted line having square symbols. A curve showing the gating of particles having a charge magnitude of -2.31fC is shown by a dash-dot line having triangle symbols. A curve showing the gating of particles having a charge magnitude of -3.07fC is shown by a dashed line having diamond symbols. A curve showing the gating of particles having a charge magnitude of -3.84fC is shown by a dashed line having inverted triangle symbols. A curve showing the gating of particles having a charge magnitude of -4.61fC is shown by a dash-dot-dot line having diamond symbols. A curve showing the gating of particles having a charge magnitude of -5.38fC is shown by a dashed line having X-square symbols. A curve showing the gating of particles having a charge magnitude of -6.14fC is shown by a dashed line having X-circle symbols.

[0080] FIGURE 19 is a graph of gated particles versus charge per diameter dimension of the particles. The results of this chart were obtained under the same conditions as discussed in FIGURE 18 with regard to the quantity of gated particles at a time of 5ms. A curve showing the gated particles as a function of charge per diameter dimension is indicated by the solid line. As such, it will be appreciated that the number of gated particles increases as the magnitude of the charge on the particles increases. It will be appreciated, therefore, that particles can be selectively gated by optimizing the magnitude of the charge thereon.

[0081] FIGURE 20 is a graph of gated particles versus time for particles having a fixed charge magnitude and a varied diameter dimension. The results were obtained under conditions in which particles having varied sizes and a -3.07fC charge magnitude were gated through a 50 μm diameter aperture. The two-phase gate included electrodes separated by 25 μm with a +400V voltage applied across the electrodes. A curve of particles having a 1.9 μm radius is shown as a solid line with circle symbols. A curve of particles having a 2.9 μm radius is shown as a dotted line with square symbols. A curve of particles having a 3.9 μm radius is shown as a dash-dot line with triangle symbols. A curve of particles having a 4.9 μm radius is shown as a dashed line with diamond symbols. A curve of particles having a 5.9 μm radius is shown as a dashed line with inverted triangle symbols. A curve of particles having a 6.9 μm radius is shown as a dash-dot-dot line with diamond symbols. A curve of particles having a 7.9 μm radius is shown as a dashed line with X-square symbols. A curve of particles having a 8.9 μm radius is shown as a dashed line with X-circle symbols. A curve of particles having a 9.9 μm radius is shown as a dotted line with X-diamond symbols.

[0082] FIGURE 21 is a graph of gated particles versus charge per diameter dimension where the charge is fixed and the diameter dimension is varied. The results were obtained under the same conditions as that for the results in FIGURE 20. This graph is a plot of the number of gated particles at 5ms for each of the curves shown in FIGURE 20. It will be appreciated from FIGURE 20 that the number of particles gated increases as the size of the particles decrease. As such, particles can be selectively gated by optimizing the aperture size and particle size. Additionally, other characteristics can be used, such as charge magnitude, for example, in the alternative or in combination to selectively gate particles.

[0083] FIGURE 22 is a graph of the number of gated particles versus particle radius. The results of this chart were obtained under the same conditions as FIGURES 20 and 21. The curve in FIGURE 22 further illustrates that the number of particles gated increases as the size of the particles decreases.

[0084] FIGURE 23 schematically illustrates particles from a particle cloud **PA** being urged through a passage, such as being gated through passage **110** by a gate **112** having electrodes **132** and **134**. For the purposes of discussing FIGURES 24 and 25, electrode **132** has a voltage **V2** applied thereacross, and electrode **134** has a voltage **V1** applied thereacross.

[0085] FIGURE 24 is a graph of gated particles versus time where the voltage of one of the electrodes of the gate is varied. The results of FIGURES 24 and 25 were obtained under conditions in which a constant supply of 400 particles in air at 2 percent by volume were provided. The particles had a radius of about 2.9 μm and a charge magnitude of about -3.07fC. The aperture had a diameter of about 50 μm and the electrodes were spaced about 25 μm apart. The voltage **V1** applied to electrode **134** was 400 V. A curve showing the number of gated particles with electrode **132** having a voltage **V2** of 400 V is shown by a dashed line with circle symbols. A curve showing the number of gated particles with electrode **132** having a voltage **V2** of 300 V is shown by a dotted line with diamond symbols. A curve showing the number of gated particles with electrode **132** having a voltage **V2** of 200 V is shown by a dashed line with square symbols. A curve showing the number of gated particles with electrode **132** having a voltage **V2** of 100 V is shown by a dash-dot-dot line with inverted triangle symbols. A curve showing the number of gated particles with electrode **132** having a voltage **V2** of 0 volts is shown by a dashed line with triangle symbols.

[0086] FIGURE 25 is a graph of particle fractions versus time for results obtained under the same conditions as the results shown in FIGURE 24. A curve showing particle fractions for a voltage **V2** of 400 V is indicated by a dotted line with square symbols. A curve showing particle fractions for a voltage **V2** of 300 V is indicated by a dashed line with diamond symbols. A curve showing particle fractions for a voltage **V2** of 200 V is indicated by a dashed line with inverted triangle symbols. A curve showing particle fractions for a voltage **V2** of 100 V is indicated by a dash-dot line with circle symbols. A curve showing particle fractions for a voltage **V2** of 0 volts is indicated by a dashed line with triangle symbols.

[0087] FIGURE 26 illustrates a voltage pattern for use on a gate having first and second electrodes, as discussed hereinbefore, with a third electrode spaced therefrom. The first and second electrodes respectively having voltages **V1** and **V2** applied thereacross. The third electrode having a DC voltage **VDC** applied thereacross. Such an arrangement is suitable for improving the response time of a gate, as the gate is turned on and turned off, as shown in FIGURES 27 and 28.

[0088] FIGURE 27 is a graph of gated particle fractions versus time as a gate is turned on for various **VDC** voltages. A curve for a **VDC** voltage of +1000 V is indicated by a solid line. A curve for a **VDC** voltage of 0 volts is indicated by a dashed line with square symbols.

[0089] FIGURE 28 is a graph of gated particle fractions versus time as a gate is turned off for various **VDC** voltages. A curve for a **VDC** voltage of +1000 V is indicated by a dashed line with squares symbols. A curve for a **VDC** voltage of 0 volts is indicated by a solid line. The results shown in both FIGURES 27 and 28 were obtained under like conditions in which particles having 2.9 μm radius and -3.07fC charges were gated through an aperture having 50 μm diameter with the electrodes

spaced 50 μm apart. The gate operated at a frequency of 1kHz with voltages of **V1** and **V2** at 400 V.

[0090] As schematically indicated in FIGURE 29, gaseous fluid flow can be used to create hydrodynamic drag through passage **110** to balance the upward effects of coulomb forces of particles **PA**.

[0091] FIGURE 30 is a graph of gated particles versus airflow velocity through an aperture. The results shown in FIGURE 30 were obtained under conditions in which a constant supply of 100 particles was provided. A curve for an aperture having a 25 μm length is shown by a solid line. A curve for an aperture having a 50 μm length is shown by a dashed line. It will be appreciated from FIGURE 30 that a fluid flow having a velocity of 20 cm/s will substantially counter the effects of the coulomb forces and substantially shut off particle flow through the passage.

[0092] FIGURE 31 illustrates a voltage pattern for voltages **V1** and **V2** applied to electrodes of a gate as discussed hereinbefore. This voltage pattern is one example of a suitable voltage pattern for shutting off particle flow through a passage in combination with the use of gaseous fluid flow.

[0093] While considerable emphasis has been placed on the preferred embodiments of the invention illustrated and described herein, it will be appreciated that other embodiments can be made and that many modifications can be made in the embodiments shown and described without departing from the principles of the present invention. Obviously, such modifications and alterations will occur to others upon reading and understanding the preceding detailed description, and it is intended that the subject invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof. Accordingly, it is to be distinctly understood that the foregoing

descriptive matter is to be interpreted merely as illustrative of the invention and not as a limitation.